Nature, Nurture or Not Sure?
A Debate About SGRs and AXPs

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Abstract. Marsden, Lingenfelter, Rothschild & Higdon have given arguments against the magnetar model for Soft Gamma Repeaters (SGRs) and Anomalous X-ray Pulsars (AXPs), as forcefully advocated by R. Rothschild at this meeting. We critique these arguments, showing: (1) The claim that SGRs and AXPs are born in unusually dense regions of the ISM is not supported in any compelling way by observations. (2) Even if this claim were true, it would not argue against the magnetar model. Moreover, all observations can be accounted for if magnetars have shorter observable lifetimes than do radiopulsars, in agreement with theoretical expectations, but no systematically different ambient ISM densities. (3) The suggestion that accretion onto the neutron star is directly influenced by the ISM in a way that explains the difference between SGRs/AXPs and radiopulsars, is not possible. The mass inflow rate during later stages of supernova remnant expansion when accretion can be influenced by backpressure from the ISM is many orders of magnitude too small. (4) Accretion-based models are unable to account for the hyper-Eddington bursts and flares which are the defining characteristic of SGRs. (5) Accretion disk models also predict optical and IR emission with higher luminosities than are observed.

1   Introduction

Marsden *et al.* present observational evidence, culled from the literature, to show that SGRs and AXPs are associated with supernova remnants (SNRs) expanding into unusually dense parts of the interstellar medium (ISM). They claim that this disproves the magnetar hypothesis [20]: "...the environments surrounding SGRs and AXPs are significantly different than 'normal' neutron stars in a way which is *inconsistent* with the hypothesis that the properties of these sources derive solely from an innate characteristic such as a superstrong magnetic field."

Marsden *et al.* go on to claim that everything about SGRs and AXPs, including their bursting behavior, can be explained if these objects are $B \sim 10^{12}$ G neutron stars accreting from SNRs in high-density regions of the ISM.

Three different version of the Marsden *et al.* paper were widely distributed and posted on the astro-ph archives [20,21,22]. We will discuss arguments from all three versions, since R. Rothschild gave arguments from all three versions at this meeting. (See Rothschild's contribution to this volume).

In §2 of this paper, we show that most of the associations of SGRs and AXPs with SNRs claimed by Marsden *et al.* are subject to reasonable doubt. Moreover, the SNR remnant ages have very large uncertainties, spanning more than an order of magnitude, if one assumes no *a priori* knowledge of the ISM ambient

density. This means that the value of the ambient ISM density is not strongly constrained by SNR measurements, even if all the proposed SNR associations are assumed to be valid. We conclude that there is no persuasive evidence for the hypothesis that SGRs and AXPs are born in regions of the ISM with unusually high density.

In §3 we show that, even if it *was* proven that SGRs and AXPs are born in denser ISM environments than radiopulsars, this would not necessarily argue against the magnetar model. We also offer an alternative interpretation of the data. Although the data set of Marsden *et al.* does not unambiguously constrain ambient ISM densities, it does give some evidence that observed SGRs/AXPs are associated with more compact (smaller-radius) SNRs than are radiopulsars on average. This can be naturally understood if SGRs/AXPs have comparatively short observable lifetimes, as expected in the magnetar model.

In §4 we turn to a scenario discussed by R. Rothschild at this meeting, namely that accretion onto a neutron star is directly influenced by a dense ambient ISM in a way that can explain all differences between SGR/AXPs and radiopulsars. The rate of accretion onto a high-velocity neutron star from a SNR in the late stages when it experiences significant backpressure from the ISM is quantified. The resulting values of $\dot{M}$ are too small by many orders of magnitude to drive the stellar spindown or the X-ray emissions of SGRs and AXPs. Thus the answer to "Nature or Nurture?" question is clearly "Nature."

This alone does not necessarily mean that the stars are magnetars. Alternatives to the magnetar model which posit accretion from a "fallback disk" which is formed at very early times within the SNR from co-moving ejecta—when the immediate environment of the neutron star is not directly influenced by the surrounding ISM (again, not "Nurture")—are also possible. This scenario was proposed by Chatterjee, Herquist and Narayan and by other authors [1].

In the concluding section (§5) we briefly summarize some general arguments against accretion-powered models of SGRs an AXPs. This evidence seems to exclude the theoretically reasonable "fallback disk" models as well as the more dubious "pushback disk" models suggested by Marsden *et al.*

2   Observational Evidence for a Dense ISM around SGRs/AXPs?

The method of Marsden *et al.* is as follows. They begin by adopting (in most cases, dubiously) a particular SNR association for each SGR and AXP. Given the SNR's measured angular size, θ_{snr}, published estimates of the distance D to each object imply a SNR radius $R = \theta_{snr}D$. If the age t of the SNR is known, then the density into which the supernova expands can be estimated via the Sedov solution, which in c.g.s. units is $\rho = 1.17\,E\,R^{-5}\,t^2$. Figure 3 in ref. [22] shows SGR and AXP points plotted on the $R-t$ plane, along with contours of constant ambient density, defined according to the Sedov formula where one assumes $E = 10^{51}$ erg. A similar process is done for radiopulsars (Fig. 4), leading to the

claim that the two sets of data are significantly discrepant, with radiopulsars in lower-density regions of the plane.

This is dubious. First of all, the R^{-5} dependence of ρ implies a D^{-5} dependence on the inferred density. If D goes up by 2, ρ goes down by 30. Many or most of the D values are uncertain by factors of 2. This is true even when the measurement uncertainty is as small as 10%, as quoted by Corbel *et al.* in their elaborate arguments for two SGR distances [5,6], because systematic uncertainties in data interpretation can exceed measurement uncertainties. It is notoriously difficult to unambiguously determine the distances of molecular clouds along lines of sight extending across the Galactic disk.

Furthermore, the ages t are very poorly constrained. The usual way to determine the age of a SNR is to assume something about the ambient density, and use the Sedov solution. Here this cannot be done since the density is the quantity that we ultimately want to determine. For most objects, Marsden *et al.* adopt a lower limit on the age given by $\min\{t_{fe}, t_v\}$, where $t_{fe} = D_{min}\theta_{snr}/v_{ej}$, and $t_v = D_{min}\theta_*/v_{max}$. In these equations, $v_{ej} = 10,000$ km s^{-1} is the assumed ejecta velocity, θ_* is the angular displacement of the star from the SNR center, and $v_{max} \equiv 2000$ km s^{-1}. But in every case t_v is greater than t_{fe}, so t_v is effectively the lower limit. This is the time that a star moving at a transverse velocity v_{max} would move from the center of the SNR to its present location, at a distance D_{min}, the minimum plausible value of D. But the center of the SNR can only be roughly fixed since the SNRs generally show deviations from sphericity and inhomogeneities. Moreover, the choice of 2000 km s^{-1} is arbitrary; larger velocities cannot be excluded. The logic of using an X-ray star's assumed velocity to infer a lower bound to the density of the environment seems convoluted. The estimate t_{fe}, never applied, would have the error bars extend much further to the right, to the *Free Expansion* line in Fig. 3 at $D = D_{min}$. This is a believable lower bound; it shows that the possible ages span orders of magnitude. The upper limits of 3 kyr for all but three points are also essentially arbitrary: "we choose 30 kyr, which is the maximum estimated age [value of $(P/2\dot{P})$] for the SNR/radiopulsar associations in Table 3." Why is it a reasonable to use the maximum age of a completely distinct set of objects?

In the three cases where detailed modeling of the SNR has been done, the error box is chosen to span the range of published values from models. But this underestimates the uncertainty also: each estimate really has an uncertainty itself, based on the data and methods used. This might not quoted, since it is hard to estimate; but there is no reason to think that it is smaller than the range of quoted ages, at least not without studying the issue.

By plotting each point at the arithmatic (not logarithmic) center of an error range that spans more than an order of magnitude (see Fig. 3 of ref. [22]), one fosters the impression that the density lies at the high end of the (claimed) permitted range. The true uncertainties are certainly not Gaussian or even log-Gaussian. Thus the data should really be plotted as error boxes, each extending horizontally across most of the plot. This would convey the fact that we have almost no information about the ages of these objects that is independent of

assumptions about ambient density. The possible values of ambient density inferred from the SNRs also span orders of magnitude.

Note that for radio pulsars (Fig. 4), Marsden *et al.* say: "The MDR timing ages of radio pulsars, unlike those for SGRs and AXPs, are thought to be good measures of their true ages." However, Gaensler and Frail, ref. [11], have shown that the true age of PSR B1757-24 exceeds 39,000 yrs, and has most probable value of 170,000 yrs, which is more than 10 times its MDR age, $t_{mdr} \equiv P/2\dot{P}$. This suggests that the MDR ages used in Fig. 4 are lower bounds, and the inferred densities are thus lower bounds on the true densities.

Finally, many of the adopted SNR associations are themselves dubious. Among AXPs, only 1E 1841-045, 1E 2259+586, and J1845-0258 have well-established SNR associations, and it is not certain that the third object is an AXP since its $\dot{P}$ is not yet measured. For the SGRs, all SNR associations have been questioned in the literature (e.g., ref. [10]). The claimed association of SGR 1801-23 is especially dubious, since its error box is a 3.5 degree long annulus intersecting several candidate SNRs [3]. Most SGRs are located near the edge of the putative associated SNR, requiring very high-velocity neutron stars $V_{sgr} > 1000$ km s^{-1}. Note that the radio emission around SGR 1806-20 may not be SNR at all, but a synchrotron nebula fed by a LBV star [16].

3   Comparisons with the magnetar model

Even if SGRs and AXPs *did* tend to come from denser regions of the ISM than do radiopulsars, this would not argue against the magnetar hypothesis.

Magnetars are thought to form during stellar core collapse events when the proto-neutron star is rotating rapidly enough during its convective phase, just after collapse, to support an α–Ω dynamo [7,8]. The progenitor objects may be massive stars which, for one reason or another, retain substantial angular momentum and do not transport too much angular momentum outward from the core material before collapse. Complex issues of star formation and rotational evolution (including possible binary interactions) may be involved in producing this subset of objects. Although these complexities are not fully understood, it is plausible that the magnetar-producing stars tend to supernova in regions of the ISM with somewhat different properties than radiopulsar-producing stars do. For example, if magnetars tended to result from more massive progenetor stars than did radiopulsars, they would be found preferentially among the first generation of supernovae in star-forming regions, before a hot superbubble forms. This kind of effect could explain a correlation with ambient density as claimed by Marsden *et al.*

We favor a different interpretation of the data. In the absence of independent information about the ages of the SGRs/AXPs, what Marsden *et al.* really have studied is simply *the distribution of SNR radii R,* as given by the projection of points in Fig. 3 of ref. [22] on the vertical (R) axis. A comparison of this distribution with the analogous distribution for Marsden *et al.*'s sample of radiopulsars with $t_{mdr} < 30,000$ yr. (Fig. 4; projected on vertical axis) suggests

that *SGRs/AXPs tend to be associated with smaller-R SNR than do young radiopulsars.* (Of course, this conclusion is only correct if we accept the dubious SNR–star associations.)

This could be explained by various selection effects which operate on both sets of objects. In particular, it is likely that *radiopulsars are observable for significantly longer periods of time than are SGR/AXPs.* This fact alone could account for the trend in SNR sizes.

In the magnetar model, all observable magnetically-powered emissions are likely to shut off when the liquid interior of the star cools sufficiently to halt ambipolar diffusion. Thompson and I showed that a magnetar's core temperature declines only weakly with stellar age, $T \sim t^{-1/7}$, at early times when ambipolar diffusive heating is balanced by neutrino cooling (eq. [36] in ref. [26]). This weak power-law decline turns down sharply when neutrino cooling becomes dominated by rapid photon cooling from the star's surface, essentially causing interior magnetic dissipative heating and core magnetic evolution to cease. We originally estimated that this occurs at an age $t \sim 10^6$ yrs (eq. [75] in ref. [26]). But if a magnetar has a light-element envelope, then surface photon cooling is greatly accelerated (ref. [13]), and it dominates the thermal history sooner, freezing out ambipolar diffusion. A magnetar could then become X-ray dark and burst–quiet as early as $\sim 10^4$ or 10^5 years (C. Thompson, private communication) with a strong magnetic field $B_{core} > 10^{14}$ G frozen in its core thereafter, decaying only on the enormously long time-scales of ohmic diffusion. This "early death" could account for the narrow observed period range of X-ray bright SGRs and AXPs, due to observational selection effects in both steady X-ray emissions and bursts. No true decay of B_{dipole} must be invoked (cf. ref. [4]).

In the case of radiopulsars, the lifetime to spin down past the radio death line undoubtedly exceeds the time for SNR fading and dispersal, by several orders of magnitude. If some magnetars become undetectable before their SNRs do, then radiopulsars would tend to have older and larger SNRs than (observed) magnetars, even if the ambient density and SNR evolutionary tracks were identical for the two classes of neutron stars.

We conclude this section with a note about implications of this picture. Because magnetar activity is ephemeral, slowly-rotating *dead magnetars* with large magnetic dipole fields should be common in the Galaxy. Indeed there could be $> 10^7$ of them if a substantial fraction of all neutron stars are magnetars, as suggested by studies of all neutron stars known to be associated with young SNRs [17]. Detecting dead magnetars is a challenging problem for astronomers.

4   Propeller-driven spindown in a dense ISM?

Marsden *et al.* propose an alternative theory: that interaction of a 10^{12} G neutron star with its SNR in a relatively dense ISM can explain everything about SGRs and AXPs.

Accretion by a compact star moving through a gaseous medium is a classical problem in astrophysics, first quantified by Bondi, Hoyle and Lyttleton. Here we

only consider accretion that occurs after the ISM can influence the immediate environment of the star; i.e., accretion occurring after the reverse shock reaches the high-velocity neutron star at $t > 10^2$ years.

Quantitative estimates of this were not given in the first version of the Marsden *et al.* paper [20]. The second version [21] did include some estimates. Careful scrutiny of ref. [21] reveals that, even assuming extremely unlikely and optimistic values of all parameters, accretion influenced by the ISM fails by many orders of magnitude to produce enough inflowing material to either spin down the star in $\sim 10^4$ years or to power the observed X-ray luminosities of SGRs and AXPs. The third version of the paper [22] omits the analysis again.

It is not surprising that such "pushback accretion" does not work. A supernova is a powerful explosion and even "dense" parts of ISM (ambient density assumed to be ~ 10–10^2 gm cm^{-3}; ref. [22]) are superb vacua by laboratory standards. Thus the pushback phenomena is not very strong. Here we use some rough approximations to quantify this. More reliable analysis would require the use of detailed SNR simulations.

Since the ejecta expands nearly homologously with uniform density and nearly constant surface velocity during the initial free-expansion phase (e.g., ref. [19]), the ejecta is almost comoving with the star at early times after the star moves away from the center of the SNR. This is the epoch when a fallback (not pushback) disk might form, see e.g., ref. [1,2].

During this period the surrounding interstellar medium (ISM) has essentially no influence on the immediate environment and accretion rate of the neutron star. The time scale for the neutron star to intercept the reverse shock and first experience possible influence of the surrounding ISM, is $> 10^2$ years. By this time, the density of the ejecta declines to roughly $n(t) \simeq 10 M_\odot/[(4\pi/3)(V_F\, t)^3]$ or $n(t) \simeq 10^2\, t_2^{-3}\, V_4^{-3}$ cm^{-3}, if we optimistically scale to $t = 10^2\, t_2$ yrs. The density of the shell material is in the range between 4 times this number (on the shell side of the reverse shock) and 4 times the ISM density (on the shell side of the outer shock). This factor 4 is of course the strong-shock enhancement factor for $\Gamma = 5/3$.

The accretion rate is $\dot{M} = (2GM)^2 \rho/V^3$ where $V = [(kT/m) + V_*^2]^{1/2}$, for a neutron star traveling through gas of temperature T with a stellar velocity relative to the gas V_* (e.g., ref. [24]) For $M = 1.4\, M_\odot$, $V_* = 10^3\, V_3$ km s^{-1} and cold gas with density $\rho = mn$, where $n = 10^2\, n_2$ cm^{-3}, one finds $\dot{M} = 7 \times 10^7\, n_2\, V_3^{-3}$ gm s^{-1}. It is less for hot gas. In $10^4\, t_4$ years, as the star crosses the SNR shell, this would accumulate only $10^{-14}\, n_2\, t_4\, V_3^{-3} M_\odot$, even if the density declined no further and the gas were not shock-heated.

The $\dot{M}$ needed to drive propeller spindown with $(\dot{P}/P) = 1 \times 10^{-11}$, as found for SGRs [18], is $\dot{M} = 4 \times 10^{16}\, B_{12}^{-8/3}\, (\dot{P}/[P \times 10^{-11}])^{7/3}$ gm s^{-1} (e.g., ref. [24]). Note that this is somewhat greater (by $\sim 10^2$) than the $\dot{M}$ needed to power X-ray emissions with luminosities $L_x \sim 10^{35}$ erg s^{-1} as observed, assuming accretion down to the surface.

Comparing the above two values of $\dot{M}$, it is evident that *accretion influenced by the ISM fails by a factor of $\sim 10^9$ for these scalings.* To get the needed $\dot{M}$,

one must have $V_* < 1.2\,n_2^{1/3}\,B_{12}^{8/9}$ km s^{-1}. Thus one needs for the gas in the SNR shell to be nearly co-moving *and* it also must be very cold, with $T < 180$ K. Neither condition is satisfied, since the shell material is significantly decelerated as soon as it crosses the reverse shock, slowing to $[(2/5)R/t]$ in the Sedov phase, and it is also shock-heated to temperatures $\sim 10^6$ K or more, as evinced by the X-rays it emits. Once the star passes outside the shell, the ISM may be cool, but it is far from co-moving. A shortfall in $\dot{M}$ by a very large factor is unavoidable.

The presence of some dust in the cooling SNR, and nonspherical gas flows, do not save the scenario. Insofar as dust grains accrete like a zero-pressure, collisionless gas, they will have much smaller $\dot{M}$, by a factor $(R_{NS}V^2/2GM)$, where R_{NS} is the neutron star's radius (e.g., §14.2 in ref. [24]). More realistically, dust will be swept along with the gas and have little effect on $\dot{M}$. As for non-spherical flows, the vast expansion factors in the SNR damp out any velocity variations except for Rayleigh-Taylor instabilities near the reverse shock, but these transient motions contain less than 1% of the SNR kinetic energy and occur in a narrow mass shell. These effects cannot make up the enormous $\dot{M}$ discrepancies quoted above.

5   Other problems with accretion-powered models

It is not known how accretion-powered models can account for the hyper-Eddington bursts and flares which are the hallmark of SGRs. The hard-gamma initial spikes of giant flares with peak luminosities $\sim 10^7\,L_{\rm Edd}$, lasting several tenths of a second, are especially difficult to account for in accretion-powered models. However, the observed properties of SGR outbursts are consistent with magnetically-driven instabilities on magnetars [25,9,12,27].

Furthermore, if SGRs and AXPs have accretion disks then they should emit optical and infrared radiation, due to the reprocessing of X-rays and viscous dissipation within the disk itself. The luminosity of this emission is not sensitive to the disk composition, as long as the disk is optically thick. Observations of optical and IR emission from several SGRs and AXPs (e.g. ref. [14,15]) find luminosities far below the predictions of disk models (e.g. ref. [23]).

References

1. P. Chatterjee, L. Hernquist, R. Narayan: ApJ, **534,** 373 (2000)
2. R.A. Chevalier: ApJ, **346,** 847 (1989)
3. T.A. Cline et al.: ApJ, **531,** 407 (2000)
4. M. Colpi, U. Geppert, D. Page: ApJ, **529,** L29 (2000)
5. S. Corbel et al.: ApJ, **478,** 624 (1997)
6. S. Corbel et al.: ApJ, **526,** L29 (1999)
7. R.C. Duncan, C. Thompson: ApJ, **392,** L9 (1992)
8. R.C. Duncan, C. Thompson: 'Magnetars'. In: *High-Velocity Neutron Stars and Gamma-Ray Bursts*, ed. by R.E. Rothschild, R.E. Lingenfelter (AIP Conference Proc. 366, New York 1996) pp. 111–117

9. M. Feroci, K. Hurley, R.C. Duncan, C. Thompson: ApJ, **549** in press (2001)
10. B.M. Gaensler: 'Anomalous X-ray Pulsars and Soft Gamma Repeaters in Supernova Remnants'. In: *Pulsar Astronomy – 2000 and Beyond*, ed. by M. Kramer, N. Wex, R. Wielebinski (Astron. Soc. Pac. 2000)
11. B. Gaensler, D.A. Frail: Nature, **406,** 158 (2000)
12. E. Gogus et al.: ApJ, **532,** L121 (2000)
13. J.S. Heyl, L. Hernquist: ApJ, **489,** L67 (1998)
14. F. Hulleman, M.H. van Kerkwijk, F.W.M. Verbunt, S. Kulkarni: Astron. & Astroph., **358,** 605 (2000)
15. F. Hulleman, M.H. van Kerkwijk, S. Kulkarni: Nature, **408,** 689 (2000)
16. K. Hurley et al.: ApJ, **523,** L37 (1999)
17. V.M. Kaspi: 'Neutron Star/Supernova Remnant Associations'. In: *Pulsar Astronomy – 2000 and Beyond*, ed. by M. Kramer, N. Wex, R. Wielebinski (Astron. Soc. Pac. 2000)
18. C. Kouveliotou et al.: Nature, **393,** 235 (1998) C. Kouveliotou et al.: ApJ, **510,** L115 (1999)
19. M.S. Longair: *High Energy Astrophysics, Vol. 2*, 2nd ed. (Cambridge University Press, Cambridge 1994) §19.4 and Fig. 19.5.
20. D. Marsden, R.E. Lingenfelter, R.E. Rothschild, J.C. Higdon: *Nature or Nurture: The Origin of SGRs and AXPs*, Version 1, December 1999
21. D. Marsden et al., Version 2, June 2000
22. D. Marsden et al., Version 3, December 2000; accepted for *The Astrophysical Journal*, astro-ph/9912207
23. R. Perna, L. Hernquist, R. Naryan: ApJ, **541,** 344 (2000)
24. S.L. Shapiro, S.A. Teukolsky: *Black Holes, White Dwarfs & Neutron Stars*, (Wiley, New York 1983) pp. 420-421 and references therein.
25. C. Thompson, R.C. Duncan: MNRAS, **275,** 255 (1995)
26. C. Thompson, R.C. Duncan: ApJ, **473,** 322 (1996)
27. C. Thompson, R.C. Duncan: ApJ, submitted (2001)